An Algorithm for a Real-Time Detection of Encounter Situations

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1. INTRODUCTION. Recent developments in world maritime traffic and the increased risk of marine casualties with catastrophic consequences have resulted in the progressive introduction of sophisticated VTS systems on shore and of ARPA systems used on board ship.

Contrary to the highly sophisticated equipment used for data collection in VTS systems and on board, data evaluation, including encounter detection, is undertaken almost completely by a human operator – either VTS duty personnel or ships' officers. For autonomous real-time encounter detection, a simple algorithm, based on a comparison of the computed distance at the closest point of approach (D_{CPA}) with a predetermined value, is used both in VTS systems and on board. Since D_{CPA}, as a sole criterion, does not allow for various traffic situations, its application results in a number of alarms that are not acceptable as a proper detection of the encounter situation.

The different behaviour of ship's officers in various traffic situations, regarding D_{CPA}, is clearly confirmed by the data collected experimentally. These data apparently show that, in practice, ship's officers do not use the D_{CPA} as the only criterion for initiating collision avoiding manoeuvres. As an explanation of the observed behaviour during an encounter, the theory of ship domains has been proposed. Since different definitions of a domain exist (Toyoda and Fuji,[1] Coldwell,[2] Davis *et al.*[3]), in this paper the size and shape of the ship domain will be considered as defined by Goodwin.[4,5]

Consequently, in this paper, an algorithm for the real-time detection of encounter situations is proposed. The algorithm is based on the concept of the collision risk coefficient. Its primary function is the development of an autonomous warning function compatible, as far as possible, with the real behaviour of ship's officers during an encounter situation.

2. BASIC ASSUMPTIONS. In order to develop an encounter detection algorithm it is necessary to define precisely the risk of collision. The only internationally accepted definition of the risk of collision is given in The International Regulations for Preventing Collisions at Sea (COLREGS), 1972, Rule 7. Unfortunately, this definition can hardly be taken as a sound basis for developing an algorithm for the real-time detection of an encounter situation because it only suggests those considerations that should be taken into account as the most important ones. Moreover, as stated in part (d)(ii) of Rule 7, even these considerations are explicitly subject to exemptions.

Contrary to the principles of the COLREGS, where the multiple encounter situation is considered as a number of successive two-ship encounters, to develop a detection algorithm, the collision avoiding action in case of a multiple encounter situation has to be assumed as a single but complex manoeuvre. In such a situation it can be assumed that the navigator's line of reasoning will comply with the following procedure.

In the case of the multi-ship encounter, for every ship in the vicinity the navigator first has to collect the necessary data. These include the determination of relative positions, relative courses and speeds, distances at closest points of approach (D_{CPA}) and times of closest points of approach (t_{CPA}). These data can be collected using radar, or otherwise have to be estimated using bearings, shapes, lights, etc. Secondly, the navigator has to perform the data evaluation. It could be imagined that the navigator associates the presumed collision risk coefficient with each and every ship in the vicinity. If any risk coefficient is higher than the predetermined maximum acceptable value (ζ), a collision avoiding manoeuvre is necessary. Obviously, the maximum acceptable value of the collision risk coefficient is determined empirically, and is a function of the navigator's education and experience, ship types, hydrographic characteristics of the area, the traffic image, etc.

The collision avoiding manoeuvre consists of a combination of course and/or speed changes but, in each case, it must result in a decrease of the highest risk coefficient below the maximum acceptable value, providing that the risk coefficients associated with other ships in the vicinity do not exceed the maximum acceptable level during the manoeuvre or after it has been completed. We accept this as the definition of a proper collision avoiding manoeuvre in our considerations.

Following the previously described line of reasoning, in cases where a multiple encounter situation exists, the decision-making process can be explicitly expressed by the characteristic function P. This function takes only two values: 1 if the collision manoeuvre is necessary, and 0 if the collision manoeuvre is not required. It can be represented as follows:

$$P = \begin{cases} 1 & \max(Z_i) > \zeta \\ 0 & \max(Z_i) \leqslant \zeta \end{cases} \tag{1}$$

where Z_i is the collision risk coefficient associated with the ith ship.

Therefore, to develop a real-time encounter detection algorithm it is necessary to define the collision risk coefficient as a function of the data collected.

3. A DETERMINISTIC MODEL. The distance (D) between two passing ships can be expressed as a function of time (t), as follows:

$$D^2(t) = D^2_{CPA} + Vr^2(t - t_{CPA})^2 \tag{2}$$

where Vr is the relative speed between two vessels, usually expressed as follows:

$$Vr^2 = Va^2 + Vb^2 - 2\, Va\, Vb \cos(\Delta K) \tag{3}$$

where Va is own ship's speed, Vb is the other ship's speed and ΔK is the angle between their courses.

If the distance between two passing ships is expressed as a function of time, it is clear from (2) that the shape of the distance curve is a function of the relative speed Vr. Since $D^2(t)$ is a parabola with respect to t, the D_{CPA} only translates the distance curve vertically but does not change its shape. Because it can easily be accepted that in reality both factors (D_{CPA} and Vr) affect the decision-making process, the distance curve has to be transformed in order to reflect the 'natural' relation between the distance and the collision risk; that is, when the distance tends to infinity, the value of the transformed distance function should tend to zero. Consequently, when a collision occurs, the distance equals zero and the transformed distance function should have the value of 1. Therefore, the following simple transformation is proposed:

$$C(t) = \frac{1}{1 + D^2(t)} \tag{4}$$

where $C(t)$ is the transformed distance function.

In order to define the collision risk coefficient, it is necessary to select a numerical parameter of the transformed distance function with the required properties. From the given expression it is clear that, for two encounters with equal Vr, the curvature of the $C(t_{CPA})$ is greater for the one with a smaller D_{CPA}. Also, for two encounters with an equal D_{CPA}, the curvature of the $C(t_{CPA})$ is greater for the one with a greater Vr. It follows that the curvature of the transformed distance function $C(t_{CPA})$ could be taken as a measure of the collision risk. The expression for the curvature of transformed distance curve at $C(t_{CPA})$ is:

$$\frac{-2\,Vr^2}{(1+D^2_{CPA})^2} \tag{5}$$

Since the curvature of the transformed distance function will be used for comparison purposes only, the sign and the constant may be eliminated, thus simplifying the previous expression as follows:

$$\frac{Vr^2}{(1+D^2_{CPA})^2} \tag{6}$$

In order to include the time component and to obtain a risk coefficient $Z(t)$, which could be used for real-time applications, the previous expression has to be multiplied by a factor containing time as a parameter. The most natural solution is to multiply it by the value of the transformed distance function $C(t)$, because it reflects the natural relation between the distance and the collision risk. Consequently, the risk coefficient $Z(t)$ is given as:

$$Z(t) = \frac{Vr^2}{1+D^2_{CPA}}\,.\,C(t) \tag{7}$$

If the collision risk coefficient is expressed as a function of the course difference (ΔK), then its values can be drawn in the form of a polar diagram around own-ship (Figs 1, 2). The area enclosed by the curve decreases as D_{CPA} increases or if the distance between the ships increases. Also, the area increases if ship speeds are increased. The risk coefficient takes a maximum value for a head-on situation ($\Delta K = 180°$) and a minimum for overtaking ($\Delta K = 0°$). If the situations in which the distance between the ships increases are excluded (ships already passed by), the risk coefficient becomes zero only for ships with equal speeds and courses.

The shape of the collision risk curve changes with change of the speed ratio. For the ratio $Vb/Va = 0$ (passing an object with zero speed) the curve degenerates to a circle, while for the ratio $Vb/Va = 1$ and $Va > 0$ the curve becomes a cardioid given by the expression:

$$Z(\Delta K) = \frac{2\,V_A\,V_B}{(1+D^2_{CPA})^2}(1-\cos\Delta K) \tag{8}$$

Obviously, the shape of the risk coefficient curve is similar to the form accepted as a domain boundary. The most apparent difference between the collision risk curve and the shape of the domain boundary is that collision risk curve is symmetric and continuous because of the exclusion of the rules-of-the-road influence from the collision risk coefficient concept. The relationship between the risk coefficient Z and the ship domain can be described as follows. If the decision-making process follows the procedure suggested in this paper, then the distance at which the collision avoiding manoeuvre takes place and the resulting D_{CPA} should be proportional to the risk coefficient Z.

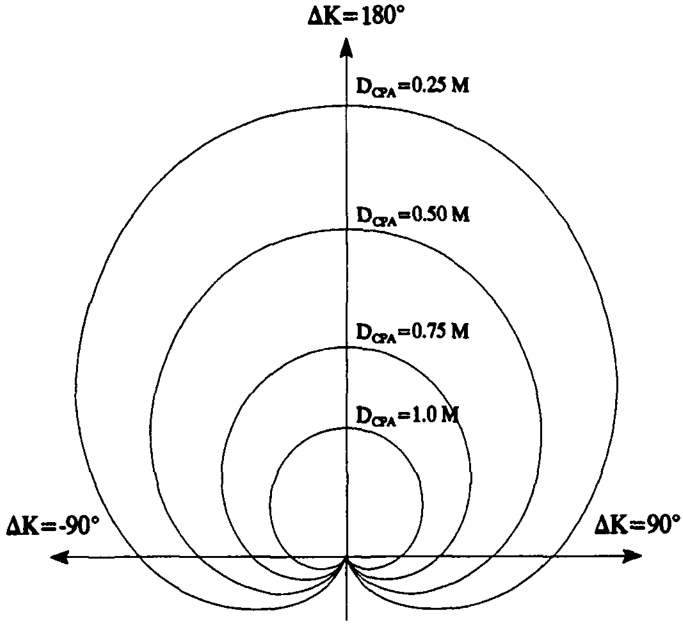

Fig. 1. The polar diagram of the risk coefficient for different values of D_{CPA} and for $Va = Vb$

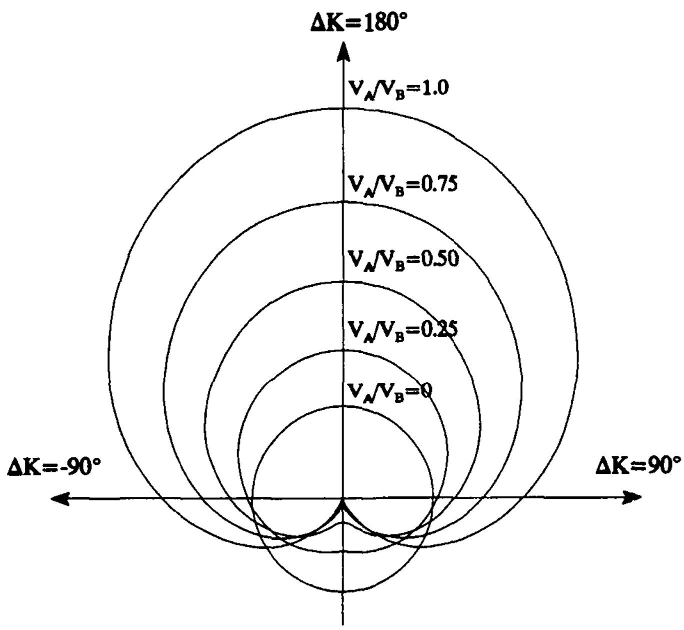

Fig. 2. The polar diagram of the risk coefficient for $D_{CPA} = 0$ and different ratios of Va/Vb.

Consequently, the collision risk coefficient can be accepted as a deterministic approximation of the ship domain concept. Nevertheless, any further conclusions regarding the interrelation between the collision risk coefficient, as suggested, and the ship domain concept requires additional research.

Consequently, from expressions (1) and (7) the characteristic warning function P takes its final form; that is:

$$P = \begin{cases} 1 & \max\left[\dfrac{Vr_i^2}{(1+D_{\mathrm{CPA}\,i}^2)^2}\,.\,C_i(t)\right] > \zeta \\ 0 & \max\left[\dfrac{Vr_i^2}{(1+D_{\mathrm{CPA}\,i}^2)^2}\,.\,C_i(t)\right] \leqslant \zeta \end{cases} \tag{9}$$

4. MODEL VERIFICATION. In order to verify the model presented in this paper with real behaviour, six different radar pictures have been produced on the computer screen with at least seven ships around own-ship. The pictures show different navigational situations appropriate to the experiment. These pictures were presented to 44 masters and mates with at least seven years of a seagoing experience. The masters and mates had the possibility to switch between pictures with relative or true motion vectors, according to their preferences. They had to select the three 'most dangerous' vessels according to their opinion. No further explanations nor any additional numerical data was given to them. The meaning of the term 'the most dangerous' was intentionally left unexplained.

Answers have been normalized in such a way that, from each answer, 'the most dangerous vessel' yields three points, the second one two points and the last one only one point. For every situation the list resulting from the experiment has been compared with the list where ships are ranked according to the risk coefficient as suggested. In all the presented situations, both lists, ranked on the one hand according to the collision risk coefficient and by masters and mates on the other, the first three positions are occupied by the same ships. In two situations an exact match has been achieved. Positions of the ships were found to interchange as follows: positions two and three in one situation, positions one and two in another and positions one and three in yet another situation. All the three positions are reversed in only one situation. All position exchanges are in favour of ships on the starboard side (which apparently shows the influence of the rule-of-the-road) and in cases where differences between risk coefficient values are not significant.

The experiment shows that, in general, the model satisfies the requirements, but it is not free of deficiencies. One of the most important is that it does not take into account the influence of the existing COLREGS. Consequently, the results of the experiment presented in this paper should be taken as an indication that further research in this direction could be valuable. Nevertheless, it is the author's opinion that, even in this form, the collision risk coefficient, as proposed, can be used as a basis for a real-time warning function.

5. CONCLUSION. The algorithm presented in this paper can be used for the real-time detection of encounter situations. Because of its simplicity, the warning function based on the algorithm is suitable for implementation on board ship, as a function of the shipboard radar, as well as a part of VTS surveillance systems. However, further field research is necessary in order to include into the model the effects of the Collision Regulations.

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KEY WORDS

1. Risk analysis. 2. Collision avoidance. 3. Marine traffic.

The Editor *writes*

The idea of producing an algorithm for the detection of encounter is a useful one, but it is not clear why the author has chosen this particular form. It might have been preferable to have made some simple assumptions, such as taking the risk to be proportional to the relative velocity V_r, inversely proportional to the distance of closest point of approach D_{CPA}, and inversely proportional to the range $D(t)$. This would lead to an expression of the type:

$$\text{Risk} = k.\, V_r/[D(t).\, D_{CPA}]$$

This could then be normalized and, if required, arranged to vary between the limits of zero and unity.